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ATMOSPHERIC DENSITY VARIATIONS AT 140 KM
DEDUCED FROM PRECISE SATELLITE
RADAR TRACKING DATA

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SUMMARY

The technique of evaluating density values from precise radar tracking data of satellites in the altitude region 130 to 140 km is discussed. Inclinations of these satellites were between 106 and 112 degrees. All elements of the density reduction technique were examined in detail, with consideration given to recent advances in geodesy, drag coefficient modeling, and orbit determination techniques. Ten days of high resolution density data deduced from orbital decay of each of three satellites are presented. Three types of density variations at 140 km are discernible in these data: (1) periodic daily density variations with a density amplitude of about 10 percent; (2) density increases of up to 35 percent associated with enhanced geomagnetic activity during which the planetary geomagnetic index, K_p , reached a value of eight units; and (3) an observed semiannual variation of about 20 percent, which indicates a total semiannual variation of 35-40 percent. These variations are discussed and compared with other results.

I. INTRODUCTION

Atmospheric density variations and their relationships with solar, geographical, and other parameters are well known in the altitude region between about 200 and 1200 km, primarily because of the large amount of data which have become available during the past 10 years from observations of the orbital decay of satellite in this region and, more recently, from in situ measurements of atmospheric density from research satellites [1, 2]. On the other hand, our knowledge of atmospheric variations in the altitude region between about 90 and 200 km is very limited, since satellite lifetimes at these lower altitudes are relatively short and the high cost of launching rocket-borne sensors in this region prohibits the accumulation of adequate data. Another problem in the measurement of atmospheric constituents in the lower thermosphere is the technical difficulties in accurately measuring atomic oxygen [3].

In addition to scientific reasons for increasing our knowledge of the atmosphere at altitudes below about 200 km, a more accurate depiction of atmospheric density in this region is needed for support of operational space vehicle applications, such as predicting satellite orbits and predicting trajectories of large rocket stages to insure that impact will occur only in uninhabited regions.

One existing source of low-altitude satellite orbital decay data is from the high resolution radar tracking data of Air Force satellites, some of which have perigees between 130 and 140 km. Tracking data are supplied in azimuth, elevation, and range, with an estimated error in satellite position of a few hundred feet; considering uncertainties in station locations, timing errors, and ranging errors. About 15 data passes per day are available from each satellite. Data are available from one satellite in 1966, one in 1967, six in 1968, six in 1969, and about the same number in 1970. Thus, during the time period 1968 to 1970 about 60 days of data are available each year. Since the shape, weight, and orbital elements of these satellites are precisely known, atmospheric density data of high accuracy are obtainable. The density data were reduced by the Aerospace Corporation based upon tracking data furnished by the Air Force. Financial support and initial data analyses were provided by the NASA Marshall Space Flight Center.

II. EVALUATION OF ATMOSPHERIC DENSITY

The satellite orbits were determined from the radar tracking data by numerical integration of the equations of motion, with consideration given to aerodynamic drag, lunar-solar attractions, and the earth's geopotential.

The accurate determination of atmospheric density from satellite tracking data requires consideration of the effects of several potential errors on computed density values.

1. Atmospheric models used in density determinations may have inherent errors that can introduce errors in deduced density values. The atmospheric model chosen for this study was the Walker-Jacchia model as modified by Bruce [4]. This model is the 1964 Jacchia model with a correction applied in the lower altitude region to depict density increases with geomagnetic increases, as has been indicated by available low altitude density data.

2. Drag coefficient, C_D , errors are directly transferred into errors in deduced atmospheric density values. A very careful and thorough analysis was performed to determine the drag coefficient

accurately. This study resulted in the selection of a variable drag coefficient (figure 1), which was calculated by consideration of the exospheric temperature and the altitude of the satellite at the time of the density calculation. Perfect accommodation and diffuse reflection were assumed.

3. An accurate geopotential model is necessary for a precise representation of the orbit of a satellite, to minimize errors in deduced density values caused by aliasing effects of gravity anomalies. An eighth-order and eighth-degree geopotential model was selected for all density evaluations for this study, after a comparison with a twelfth-order and twelfth-degree geopotential model indicated differences in deduced density values of less than one percent.

4. Density determinations from satellite tracking data are subject to errors from range biases, station location errors, refraction errors, and timing errors. A simulation study was conducted to evaluate the effect of these uncertainties on deduced density values.

a. Range radar biases were evaluated by fitting five overlapping one-day data spans for one satellite, using station radar range biases as additional fitting parameters in the orbit determination. In this manner, a radar range bias value was determined for each of the one-day fitting spans. The results were evaluated and found only to a small degree to be caused by atmospheric, geopotential, or station location errors. As a result of this procedure, this evaluation of radar range biases was incorporated in all satellite data analyzed.

b. The radar tracking station locations used in this study have been determined very accurately from TRANSIT information, and it has been established that errors associated with uncertainties in these values have a negligible effect on the accuracy of deduced density values.

c. Calculations of refraction errors of radar data used in this study indicate they have a negligible effect on deduced density values.

5. Probably the largest source of error in the deduced density values is due to errors in our knowledge of the drag coefficient. All studies to date indicate this error source to be less than 10 percent.

6. The time resolution of deduced density values is dependent upon the length of the orbit-fitting span used in the reduction process. A short fitting span is more representative of instantaneous values of density than a long fitting span, since more averaging occurs when fitting data over long intervals of time. On the other hand, accurate orbit determination is difficult during periods of rapidly changing density values when using short fitting spans; consequently, there has to be a trade-off between time resolution and accuracy of orbit determination.

Before the reduction of these density data, a study was conducted to determine the accuracy of density determination as a function of fitting interval. Simulated low altitude density data were generated with the Bruce atmospheric model [4] as a control. Density values were then calculated using different fitting spans. The results of this study showed that average density values could be determined with an error of less than one percent, using an orbital fitting interval of eight revolutions (12 hours) of tracking data. Eight fitting parameters were used in the orbit-fitting process--six orbital elements fit over the entire data span and two drag factors, each fit over four revolutions of data. This technique increased the time resolution of derived density values by a factor of two, since each calculated density value represents an average over four revolutions (six hours) evaluated near the center of each fit span. Fitting spans were overlapped through the data in two-revolution increments, resulting in up to 100 density values for each 10-day orbital interval. This technique also permitted a comparison of computed perigee altitude for consecutive orbit fits. These comparisons showed an average error of computed perigee altitude of a few hundredths of a km.

7. As recommended by King-Hele [5] the computed density values were assumed to valid at a height

$$Y = Y_p + 1/2 H^*,$$

where

Y = height assigned to the density observation

Y_p = height of perigee

H^* = value of the scale height, H , at perigee height.

III. RESULTS AND COMPARISONS WITH PREVIOUS RESULTS

Values of the atmospheric density deduced from tracking data of Satellites 1968-31A, 1968-47A, and 1969-7A, with corresponding values of the geomagnetic planetary index, K_p , are shown in figures 2, 3, and 4, respectively. To eliminate variations due to height changes, the density data were normalized to an altitude of 140 km, using the density of the Jacchia 1964 atmosphere as modified by Bruce [4] and the following relationship:

$$\rho_n = [\rho'_{z_0} / \rho'_z] \rho_z,$$

where

ρ_n = actual density normalized to 140 km

ρ_z = actual density evaluated at altitude z

ρ'_{z_0} = model density at altitude z_0

ρ'_z = model density at altitude z .

Initial orbital elements and other pertinent information concerning the orbits of these satellites are shown in Table 1. The breaks in the atmospheric density plots result from the unavailability of tracking data.

Table 1

Satellite	Perigee Altitude	Apogee Altitude	Inclination (deg)	Argument of Perigee (deg)	Data Span
1968 31A	137 km	455 km	112	124	4/17/68 - 4/27/68
1968 47A	130 km	465 km	112	118	6/06/68 - 6/17/68
1969 7A	135 km	1110 km	106	153	1/22/69 - 2/1/69

There was not sufficient variation in the 10.7 cm solar radio flux during the period these three satellites were in orbit to identify density variations associated with changes in the solar extreme ultraviolet radiation. It was also not feasible to detect diurnal variations associated with the solar bulge, since the orbits of these satellites were nearly sun-synchronous; i.e., the perigee point stayed at about the same local time from orbit to orbit. Atmospheric density variations that are identifiable in these data include a semiannual variation, periodic daily variations, and variations associated with geomagnetic activity.

A. Periodic Daily Density Variations

Variations of atmospheric density, with a period of about 24 hours, are evident in figures 2 through 4. The amplitude of these variations ranges from about 10 percent during periods of low geomagnetic activity to more than 25 percent during periods of high geomagnetic activity, when

the transient effects of heating associated with enhanced geomagnetic activity are combined with the periodic variations. This type of variation has been observed in most low altitude, high resolution density data of which the authors are aware.

The first reference to this variation in the open literature was by DeVries et al. [6], from analyses of eleven Agena satellites with perigee altitudes between 163 and 212 km. During periods of low geomagnetic activity, when it was possible to separate this variation from other variations, these authors found that the maximum of this variation occurred when the satellite perigees were between 0 and 30 degrees longitude. They suggested a number of possible explanations for this anomaly, such as changes in the photoionization rate caused by variations in solar extreme ultraviolet radiation, changes in high altitude circulation over different geographic regions, and orientation of the earth's geomagnetic field.

Jacobs [7] analyzed data from several of the same satellites and attributed the daily periodicity to an earth-fixed density bulge rotating through the orbit plane. The fact that Jacobs did not detect this variation from tracking data of a satellite at a perigee altitude of 350 km would indicate it to be a low altitude phenomenon. Jacobs [8] later modeled a high latitude density bulge, based on data from eleven low altitude satellites. An evaluation of this model on independent unpublished data obtained by Bruce in 1968 indicated that there was not a fixed density bulge at the geographic location suggested by Jacobs.

In a discussion of atmospheric variations possibly connected with the solar wind, Jacchia [9] suggested that a 24-hour variation in atmospheric density could result from the interaction between the corpuscular stream from the sun (the "solar wind") and the geomagnetic field of the earth due to variations in the angle between the earth's dipole geomagnetic field and the line joining the earth and the sun. Although none of the suggestions to date appear to explain completely this periodic variation, Jacchia's hypothesis appears most reasonable. These new data provide the following information concerning the characteristics of this variation:

- (1) During geomagnetically quiet periods, such as April 19-21 (figure 2), there was a 24-hour period variation, with another smaller peak occurring twelve hours after the larger one. This would support Jacchia's hypothesis that the periodicity is caused by the interaction of the earth's geomagnetic field and the solar wind.
- (2) The daily periodicity is pronounced in data from Satellite 1969-9A (figure 4), which was in an orbit with a perigee latitude near 25 degrees and a relatively high eccentricity. This supports Jacchia's [9] explanation and refutes Jacobs' [7] proposal of a fixed high latitude density bulge.

(3) There is a tendency for the highest values associated with the daily periodicity to occur near the same geographic locations during a series of successive days but for these locations to change after longer periods of time. This would also support Jacchia's [9] "solar wind" explanation.

B. Semiannual Variation

The semiannual atmospheric variation, with maxima in April and October and minima in January and July, has been observed in high altitude satellite data since shortly after the launch of the first satellites. It has only recently been observed at altitudes lower than about 200 km. There have been no previous results published on the semiannual variation in satellite data at altitudes as low as 140 km. Although it is not possible to obtain continuous data for long periods of time from this series of satellites, semiannual variations can be identified from comparisons of data during short intervals spaced throughout the year.

Atmospheric density data normalized to an altitude of 140 km as a function of the geomagnetic planetary index, K_p , for three satellites are shown in figure 5. The three straight lines represent a least squares fit to data from each satellite. A pronounced semiannual variation between April and January can be seen in figure 5, with the maximum during April exceeding the minimum during January by the ratio 1.2. Since neither of these dates coincide with the time at which the extremes of the semiannual variation at higher altitudes have been observed--July 29 for the minimum and October 27 for the maximum [10]--an extrapolation of these data to times of maximum variation would indicate a total semiannual variation at 140 km of about 35-40 percent.

C. Comparison with Other Semiannual Variations

Observed below 200 km

King-Hele et al. [11] concluded, from analysis of the orbit of Satellite 1967-31A at an altitude of 180 km during 1968 and 1969, that average density at the maximum of the semiannual variation at that altitude exceeded the minimum by a factor of 1.32. Ching [12] found a semiannual variation at 170 km of about 14 percent between August and September 1968, from analysis of the orbit of Satellite 1968-59B. Since the motion of the perigee of this satellite was such that the solar bulge was anticorrelated with the semiannual effect, the total semiannual effect could be higher at that altitude than the observed 14 percent. King-Hele et al. [5] found a ratio of the maximum to the minimum density of the semiannual variation of about 1.2 at a height of 168 km from tracking data of Satellite 1968-59A between July and October 1968. Vercheval [13] found

a semiannual variation at 155 km altitude of 40 percent between January and April 1967, from orbital data of Satellite 1966-101G. With a semi-annual variation also being observed at 90 km [14], it appears this is a phenomenon that is observed throughout the lower thermosphere.

D. Density Variations Associated with Geomagnetic Activity

Atmospheric density data in figures 2 through 5 show the atmosphere at an altitude of 140 km is responsive to variations associated with geomagnetic activity. This indicates the source of heating for this phenomenon is at altitudes lower than 140 km.

The density data shown in figure 5 are the highest values associated with various values of the planetary geomagnetic index, K_p , during the time the three satellites were in orbit. A least-squares fit to the data from each satellite indicates that the atmospheric density increases about linearly with K_p values during periods of low geomagnetic activity. The maximum variation associated with geomagnetic activity in these data was about 35 percent, when the K_p index reaches 8 units during the orbit of Satellite 1968-47A.

These results are in good agreement with those of Ching [12], who also observed a density increase of about 35 percent at 140 km from high resolution drag analysis of the OV1-15 satellite during enhanced geomagnetic activity when the K_p index reached a value of eight units. More data at low altitudes are needed to establish the nature of this relationship during periods of high geomagnetic activity.

III. CONCLUSIONS

Analysis of density data deduced from precise radar tracking data of low altitude satellites indicates a total density variation of at least 80 percent from three of the recognized types of variations--semi-annual variations, variations associated with geomagnetic activity, and a periodic daily variation. Other types of variations, such as the diurnal variation, variations with solar cycle, and transient density variations associated with gravity waves added to variations detected in these data, could result in a total density variation at 140 km of an estimated factor of between two and three. Since it is impossible to represent variations of this magnitude at lower altitudes by exospheric temperature corrections, it is necessary to incorporate them at the lower boundary of the appropriate atmospheric model. Jacchia [10] is applying such a correction to models currently being prepared for the 1971 COSPAR International Atmosphere.

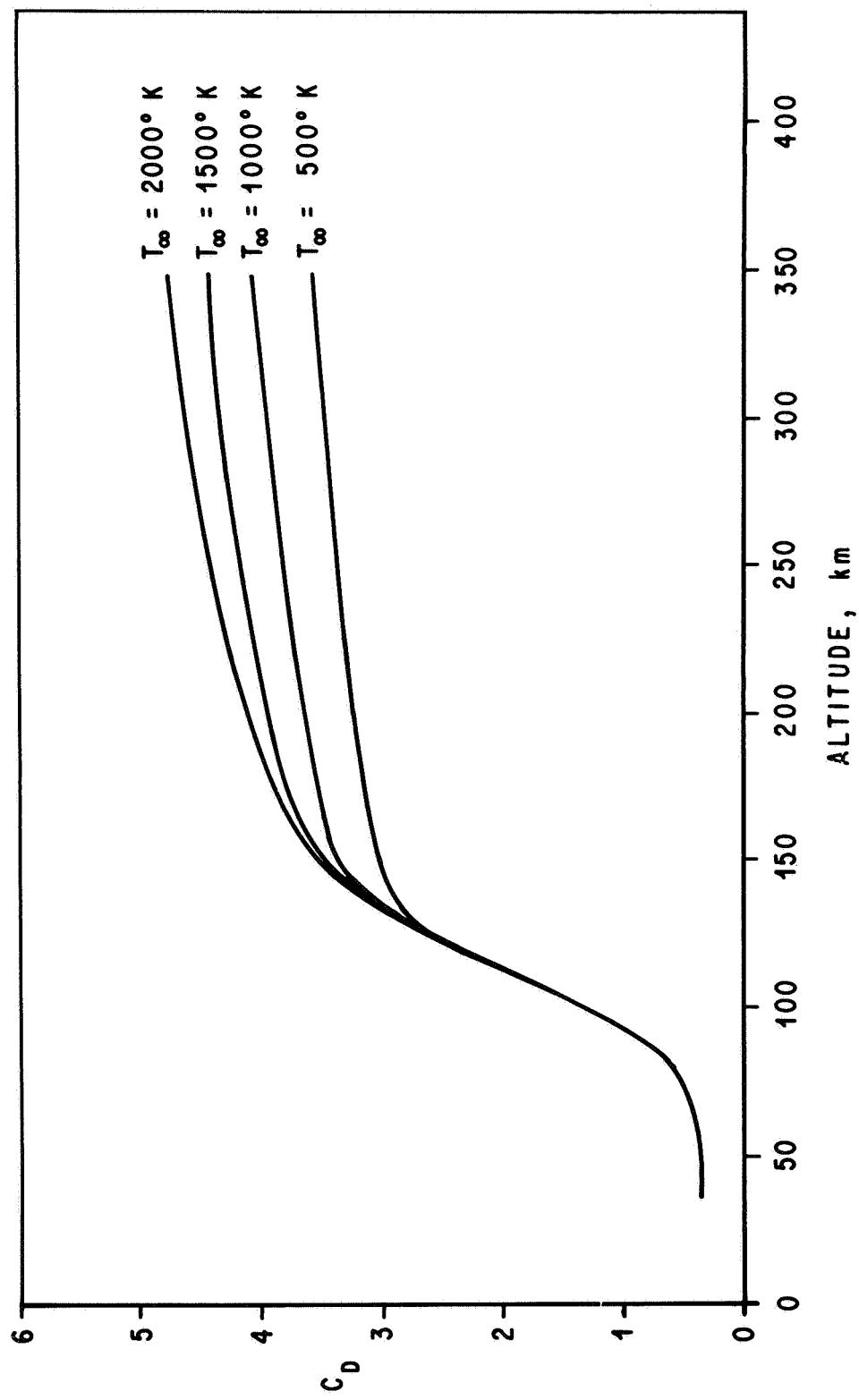


Figure 1. Drag Coefficient-Altitude Plot for Various Exospheric Temperatures

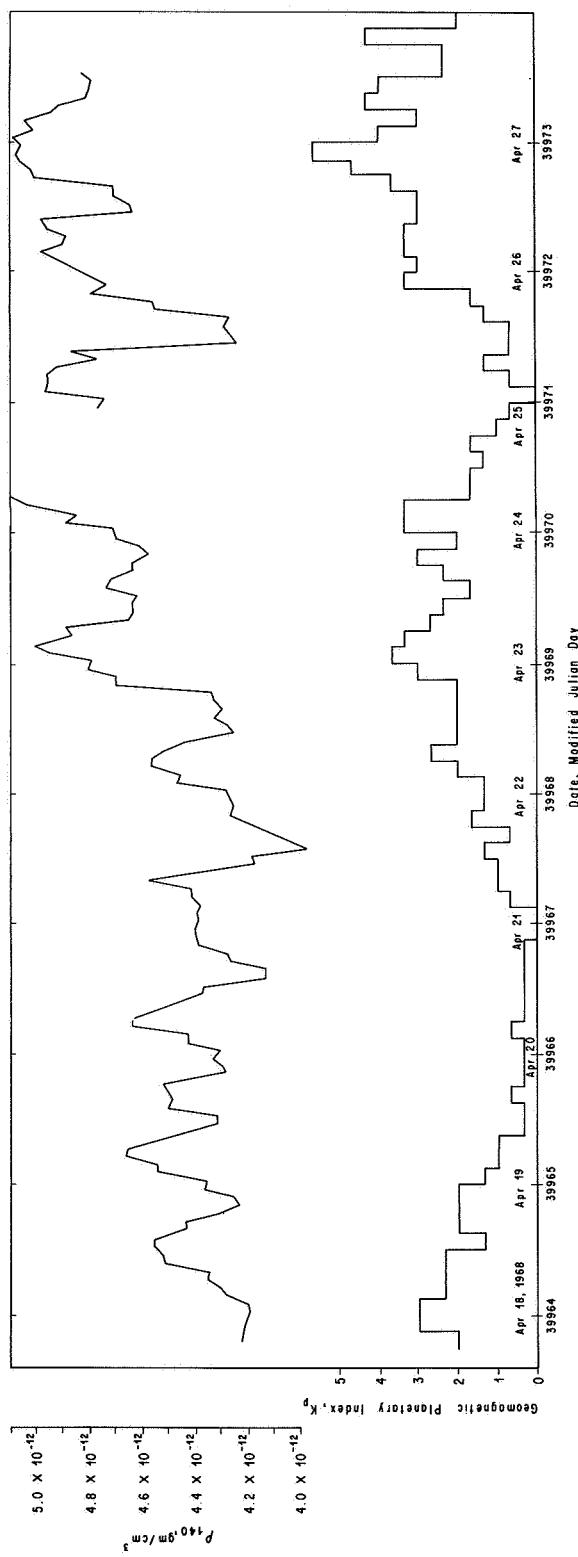


Figure 2. Atmospheric Density and Geomagnetic Activity for Satellite 1968-31A

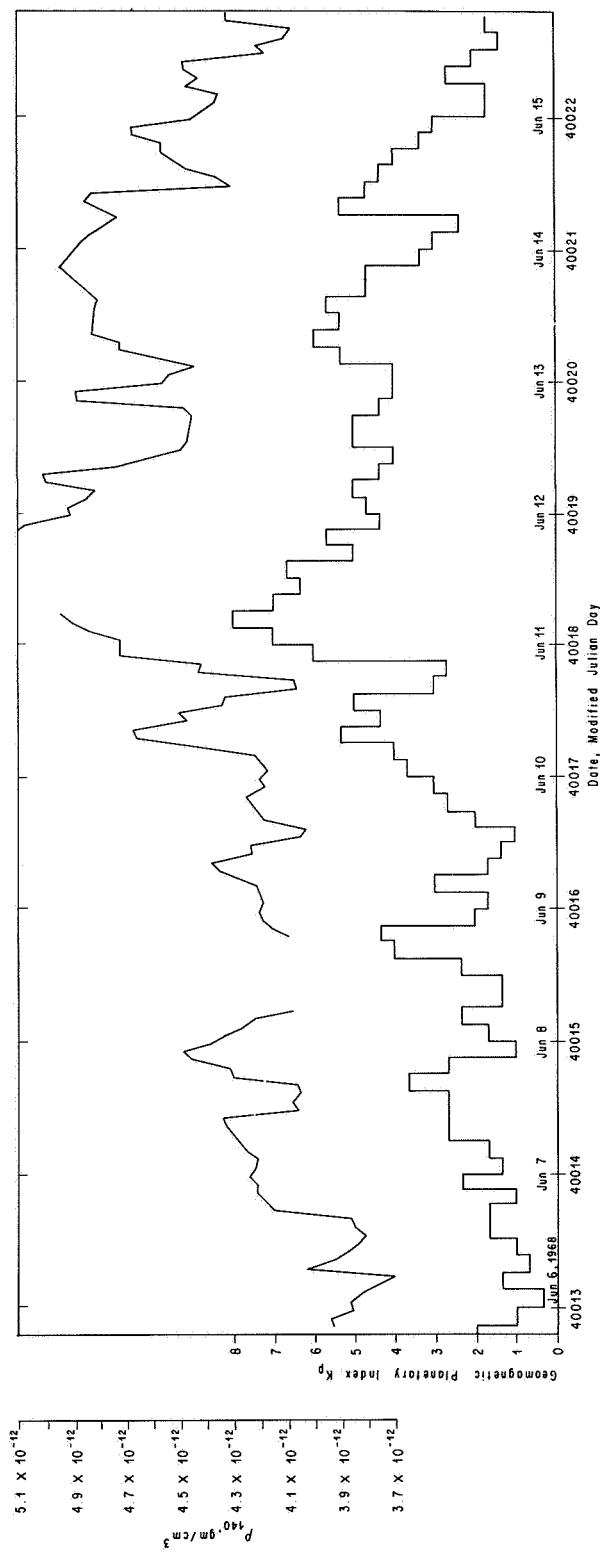


Figure 3. Atmospheric Density and Geomagnetic Activity for Satellite 1968-47A

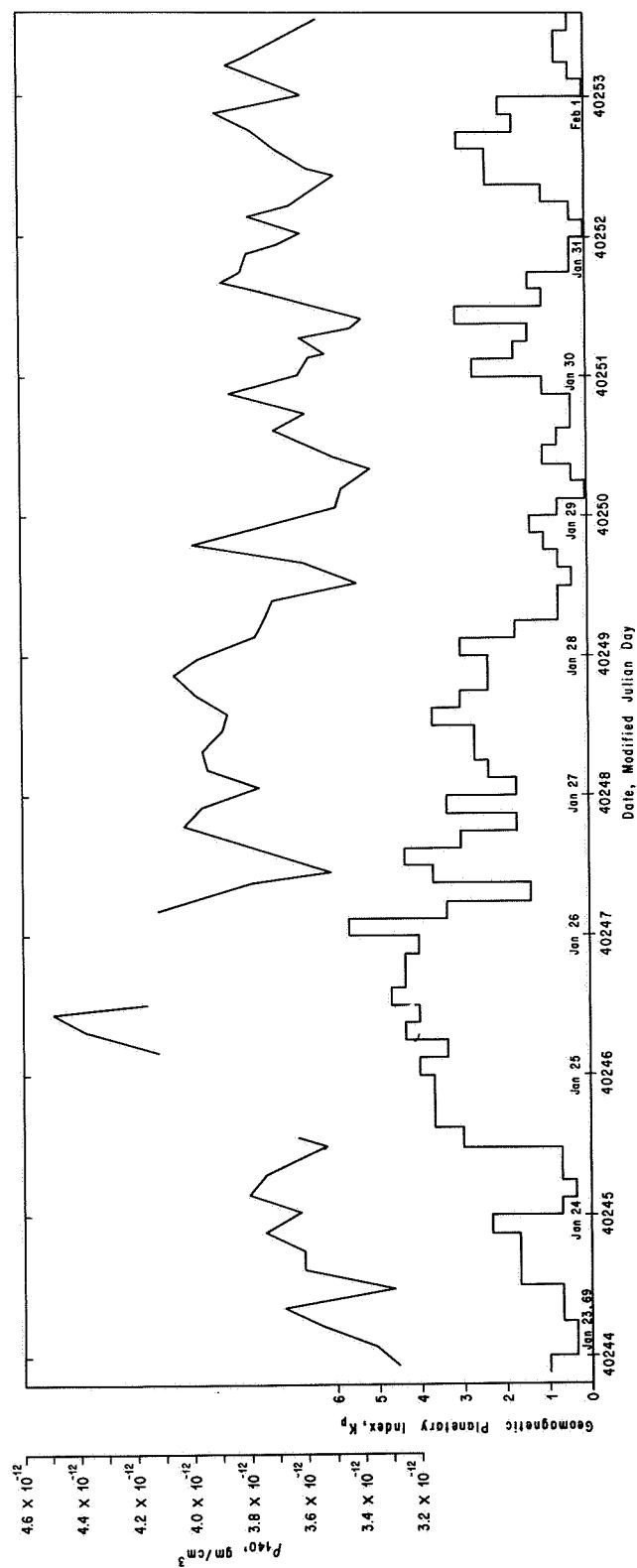


Figure 4. Atmospheric Density and Geomagnetic Activity for Satellite 1969-7A

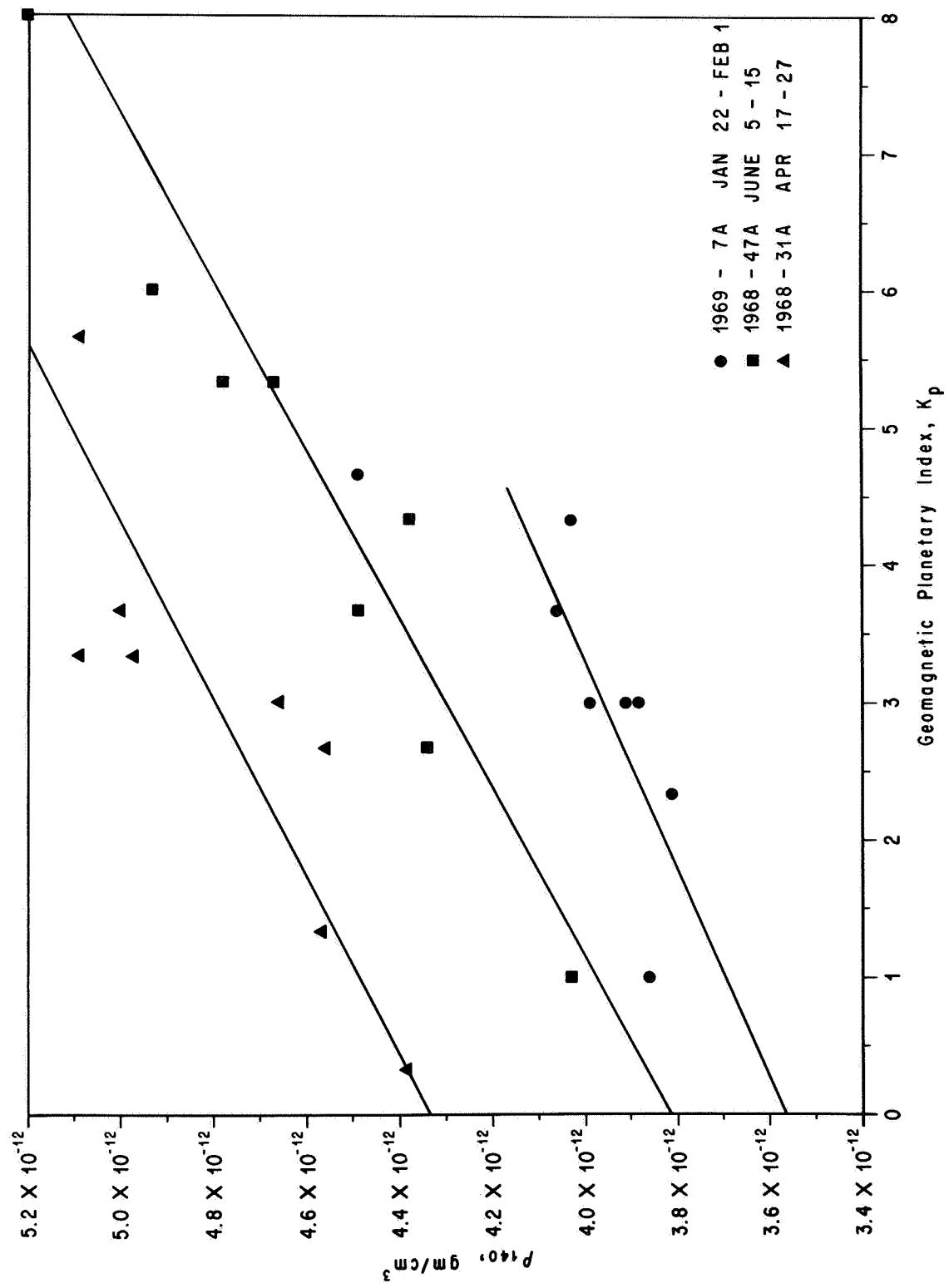


Figure 5. Atmospheric Density as a Function of Geomagnetic Activity for Three Satellites

REFERENCES

1. Pelz, D. T. and C. Newton: Midlatitude neutral thermospheric Density and temperature measurements, J. Geophys. Res. 74(1), 267-272 (1969).
2. Taeusch, D. R., G. R. Carignan, and C. A. Reber: Response of the neutral atmosphere to geomagnetic disturbances, paper presented at the XIII Plenary Meeting of COSPAR, Leningrad, USSR, 20-29 May 1970.
3. von Zahn, U.: Neutral air density and composition at 150 kilometers, J. Geophys. Res. 75(28), 5517-5527 (1970).
4. Bruce, R. W.: An atmospheric model recommended for analysis of low altitude satellite orbits, TOR-100(2110-01)-8, The Aerospace Corporation, El Segundo, California (August 1966).
5. King-Hele, D. C. and D. M. C. Walker: Air density at heights of 140-180 km from analysis of the orbit of 1968-59A, Planet. Space Sci. 17, 1539-1556 (1969).
6. DeVries, L. L., E. W. Friday and L. C. Jones: Analyses of data deduced from low altitude high resolution satellite data, Space Research VII, ed. by R. L. Smith-Rose, 1174-1182, North Holland Publishing Co., Amsterdam (1967).
7. Jacobs, R. L.: Atmospheric density derived from the drag of eleven low altitude satellites, J. Geophys. Res., 72(5), 1571-1581 (1967).
8. Jacobs, R. L.: Lockheed atmospheric density model (1967), Tracking Note #87, Lockheed Missiles and Space Co., Sunnyvale, California, February 1967.
9. Jacchia, L. G.: Influence of solar activity on the earth's upper atmosphere, Planet. Space Sci., 12, 355-377 (1964).
10. Jacchia, L. G.: New static models of the thermosphere and exosphere with empirical temperature profiles, Smithsonian Astrophysical Observatory Special Report 313 (1970).
11. King-Hele, D. G. and D. M. C. Walker: Air density at heights near 180 km in 1968 and 1969, presented at the XIII Plenary Meeting of COSPAR, Leningrad, USSR, 20-29 May 1970.
12. Ching, B. K.: Atmospheric density and rotation below 195 km from a high resolution drag analysis of the OV1-15 satellite, TR-0059(6260-10)-5, The Aerospace Corporation, El Segundo, California, October 1970.

REFERENCES (Concluded)

13. Vercheval, J.: Les variations de la densite atmospherique vers 150 km deduires de l'Etude du Freinage des Satellites," Ann. Geophys., 25, 405-417 (1969).
14. Cook, G. E.: Semi-annual variations in density at a height of 90 km, Nature, 222, 969-971 (1969).

APPROVAL

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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